CHAPTER 1.
INTRODUCTION

Although serious scientific investigation into flow in canals and pipes is several centuries old, the systematic study of the hydraulics of alluvial rivers began in the last part of the 19th century and accelerated in the 20th century. Alluvial rivers are important because of their many beneficial uses, including providing an avenue for navigation, conveying flood flows, providing recreation, supporting ecosystems, and providing drinking water. This research has centered on gaining additional understanding of the hydraulics of sand-bed alluvial rivers, specifically gaining insight into the mean flow field over dunes.

1.1. Hydraulics of Sand-Bed Alluvial Rivers

An alluvial river is a water body that flows through gravels, sands, silts or clays deposited by flowing water. Natural alluvial streams usually are wide with an aspect ratio (width to depth) of 10 or greater (Yalin and da Silva, 2001) and the boundary can be molded into various configurations as was demonstrated in the seminal work by Gilbert (1914). With alluvial rivers, the channel geometry is affected not only by the flow of water but by the sediment transported by the water as well. A fundamental challenge in working with alluvial channels is understanding the dynamics of water flow and sediment transport and realizing the interdependence of both. When the flow changes, the sediment transport changes and, in turn, the channel geometry usually changes, especially in sand-bed channels. Channel-geometry changes then can affect the stage and, thus, further change in the sediment transport. Bedforms are present, mainly in the form of dunes or ripples, in large alluvial rivers. These bedforms are transient and greatly affect the resistance to flow.

The resistance to flow results in energy loss. The earliest works dealt with the cross sectional-averaged flow properties. Various forms of relating cross sectionally averaged velocity to resistance have been presented in the literature (Clemens, 1897, Prony, 1804, Manning, 1889, Weisbach, 1845) as follows:

$$U = \frac{K_n}{n} R_h^{\frac{2}{3}} S_e^{\frac{1}{2}} \text{ Manning Equation,} \quad [1.1]$$

$$U = \sqrt{\frac{8g}{f} R_h S_e} \text{ Darcy-Weisbach Equation,} \quad [1.2]$$

and

$$U = C\sqrt{R_h S_e} \text{ Chezy Equation ,} \quad [1.3]$$

where U is the mean velocity, R_h is the hydraulic radius, S_e is the energy slope, n is Mannings roughness coefficient, f is the Darcy-Weisbach friction factor, g is the acceleration of gravity, K_n is a units parameter, and C is Chezy's roughness coefficient.

The Manning and Chezy equations are the most common equations used in the United States to describe resistance to flow in open channels. The Darcy-Weisbach equation was developed for use in pipes but sometimes is used in open channels (the equation presented above is an altered version of the pipe equation so that it can be applied to open channels). All three equations were developed based on the assumption that the shear stress is proportional to the velocity squared and the energy dissipation is caused entirely by boundary resistance. Yen (1992) defines the hydraulic resistance as "…the force to overcome or the work required to be done to counter the action of the rigid, flexible, or moving boundary on the flow." The components of the resistance can be divided into various forms. Rouse (1965), in his classical paper, divided resistance into surface resistance, form resistance, wave resistance, and resistance attributable to unsteadiness. Leopold and others (1964) divide the resistance among skin friction, internal distortion, and spills. Yalin (1977A) divided the resistance into skin roughness, sand wave roughness, and resistance because of suspended sediment. Chow (1959) listed the factors affecting Manning's roughness (sic) coefficient as: surface roughness, vegetation, channel irregularity, channel alignment, silting and scouring, obstructions, size and shape of channel, stage and discharge, seasonal change, and suspended material and bed load. Yen (1992) summarizes all these various descriptions into the following categories for types of hydraulic resistance:

Surface (grain)

Form {large obstacles, bedform, channel alignment}

Wave {high froude number, nonprismatic channel, channel alignment, obstacles and large bedforms}

Wall permeability, seepage and lateral flow

Wall flexibility (i.e. vegetation)

Wall mobility {erosion, deposition}

Suspended sediment in flow

Flow unsteadiness

Much alluvial channel research concentrates on understanding surface (grain) and form resistance (or drag). Form resistance results from a net-pressure distribution over an obstacle. This pressure is normal to the surface and, as such, does not affect the movement of sediment (either by bedload or entrainment) (Garcia, 1999, p 6.47). The bed shear stress has been observed to vary with the square of the depth-averaged mean velocity as

$$\tau_0 = \rho C_f U^2 \quad , \qquad [1.4]$$

where C_f is the frictional resistance coefficient and U is the depth-averaged mean velocity.

In considering the vertical distribution of velocity, both experimentally and theoretically, the velocity distribution in conduits has been found to have a logarithmic relation as

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln z + C \quad , \qquad [1.5]$$

where u is the mean velocity at location z in the vertical, u_* is the shear velocity, κ is von Karman's constant, and C is a constant (Schlichting, 1979). This relation is a universal velocity distribution with the constant C being evaluated based on the properties of the wall or boundary surface. This relation will be discussed in more detail in Section 2.2.2.

For fully rough turbulent flow, equation 1.5 can be altered to make z scale with the roughness height (k_s), and coupling with Nikuradse's experimental data (Schlichting, 1979, p 619-620), equation 1.5 becomes

$$\frac{u}{u_*} = \frac{1}{\kappa}\ln\left(\frac{z}{k_s}\right) + 8.5 \quad , \qquad [1.6a]$$

or pulling the constant into the logarithm (for κ=0.40) yields

$$\frac{u}{u_*} = \frac{1}{\kappa}\ln\left(\frac{30z}{k_s}\right) \quad . \qquad [1.6b]$$

This form of the equation, termed the log-law in many texts (as opposed to the velocity defect law and the log-wake law), is assumed to be valid throughout the flow field. However, the log law is found to inherently be valid only in the wall region, which Nezu and Nakagawa (1993) define as z/H<0.2, where H is the mean flow depth. As noted in equation 1.5, shear velocity is used as a scaling parameter for the velocity. Because the shear velocity is related directly to the shear stress as

$$u_* = \sqrt{\frac{\tau_0}{\rho}} \quad , \qquad [1.7]$$

equations of this type are also termed flow-resistance equations. In rigid conduit flow, determining or estimating the value of the effective roughness height and shear velocity is fairly straight forward as the cross-sectional geometry and flow resistance arising from the roughness elements protruding into the flow from the walls is stable and fixed. The resistance or shear associated with small particles protruding from the surface of the boundary is known as grain shear or Nikuradse type resistance (Schlichting, 1979). For plane-bed conditions in alluvial channels, the resistance relations are similar to that for resistance in a rigid boundary channel. However, as will be discussed later, for plane-bed situations, the assumption that the roughness height can be assumed to be a Nikuradse type roughness is not necessarily correct. This assertion stems from some investigators equating the roughness height to the top of the saltating layer if sediments are being moved as bedload (Smith and McLean, 1977) (bedload being defined as sediment moving in contact with the bed by saltation, sliding, or rolling, where bedload is a function of the grain shear stress and other parameters (Garcia, 1999)).

The hydraulics of a sand-bed river cannot be discussed without considering sediment transport. The transport of sediments is divided into two categories: bed-material load and wash load. The bed-material load is defined as that part of sediment in transport whose sizes are found predominantly in the bed, whereas the wash load is defined as that part of the sediment in transport that is not found predominantly in the bed (therefore, the wash load designation implies the sediment "washes" through the reach of interest). The wash load consists of fine particles in the clay and fine silt range that tend to be kept in suspension by turbulence (Raudkivi, 1990). The particles composing the wash load enter the stream by overland flow.

The bed-material load is further divided into suspended-sediment load and bedload. If the suspended-sediment concentration and velocity distribution in the vertical are known, the following equation, as presented by Einstein (1950), enables the computation of the suspended-sediment load (q_s) as

$$q_s = \int_b^H cudz \quad , \qquad [1.8]$$

where c is the time averaged suspended-sediment concentration; u is the time-averaged turbulent fluid velocity; H is the depth of flow; b is a reference location a small distance from the bed; z is the vertical distance measured from the channel bed. A large amount of work has been done on the relations for both the suspended-sediment concentration distribution and the velocity distribution (Vanoni, 1975).

Sand is stationary on the bed of an alluvial river until some critical state of flow is realized. Shields (1936) proposed a curve of critical dimensionless shear stresses to delineate stability criteria for particular bed-material sizes. There has been dispute concerning the values of dimensionless shear stress that will cause particles to move (Garcia, 1999). Also, dispute has arisen whether the critical stress is deterministic, as purported by Shields, or rather stochastic, because of both the presence of turbulence as a main mechanism in the entrainment of particles and the hiding factor that accompanies sediment mixtures.

Once the critical state of flow has been reached, sand is transported by skipping and hopping along the bed (known as bedload or saltation load), entrained up into the water column to be part of the suspended sediment load, and re-deposited. This process usually is continuous, whereby the circularity is dependent on the following factors: flow velocity, turbulence intensity, grain shear stress, entrainment of sediment from the bed, concentration of sediment in the water column, sediment size, bedload transport, and the formation and maintenance of bed forms. Understanding this process is key to understanding the dynamics of an alluvial river. In sand-bed rivers, it is difficult at times to make the distinction completely between suspended-sediment load and bedload as the boundary between the two is not distinct.

The dynamics of the sand-bed river further is complicated by various types of bedforms occurring as a result of the interaction between the flow and the erodible bed through sediment transport. The progression of bedforms appears in two flow regimes: lower-flow regime and upper-flow regime. The lower-flow regime transition is as follows: ripples, dunes, washed out dunes (also called transition). The lower-flow regime moves into the upper flow regime, which has the following transition: plane bed, antidunes, and chutes and pools. For the sand-bed rivers of interest in this study, the lower regime will be of primary interest as the Froude numbers are less than one (usually much less than one). This result will preclude the possibility of antidunes that occur only when the Froude number approaches or is greater than one (Simons and Richardson, 1966, p J9). However, as plane beds can occur over a large range of Froude numbers ($0.3<Fr<0.8$), we may also see plane beds in this study. For shallow-water waves, or long waves, (which applies to most open-channel flow), the critical condition separating sub-critical and super-critical flow results when the Froude number (Fr) is near unity, where

$$Fr = \frac{U}{\sqrt{gH}} \quad . \qquad [1.9]$$

U is the mean velocity, g is the acceleration of gravity, and H is the mean flow depth. Dunes are not considered long waves because the wavelength is on the order of the water depth (Garcia, 1999). Through potential-flow analysis over a wavy bed by Kennedy (1963), the following was identified as the critical flow condition for flow over a bedform

$$Fr = \sqrt{\frac{1}{k}\tanh(k)} \quad , \qquad [1.10a]$$

where k is the dimensionless bedform wave number ($\frac{2\pi H}{\lambda}$) and λ is the bedform wavelength. For dunes or ripples to occur, the following condition must be satisfied

$$Fr < \sqrt{\frac{1}{k}\tanh(k)} \quad . \qquad [1.10b]$$

The flow over a field of bedforms is more complex than that of plane bed conditions. The bedforms are an obstacle in the flow and cause both wake effects downstream of the bedform and local spatial acceleration of the flow. The momentum defect caused by the bedforms diffuses outward in the downstream direction (figure 1.1) (Smith and McLean, 1977). Flow separation occurs near the crest of the bedforms followed by a reattachment of the flow on the next downstream bedform. At the reattachment point, a new internal boundary layer begins to grow within the wake region.

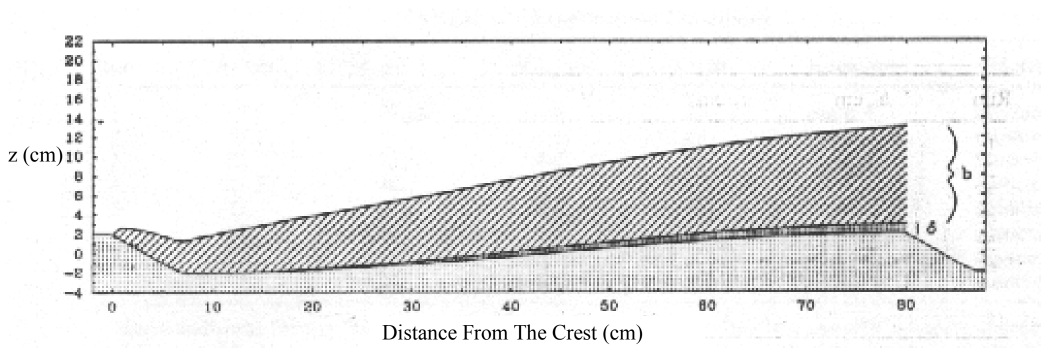

Figure 1.1—Flow over a dune, δ is the internal boundary layer and b is the wake effect resulting in a momentum defect (from Nelson and others, 1993)

The formation of bed forms, and concurrent effects on flow, result in an additional resistance component termed form resistance. Einstein (1950) presented the following partition for the components of the shear stress as

$$\tau_0 = \tau_0' + \tau_0'' \quad , \qquad [1.11]$$

where τ_0 is the total bed-shear stress, τ'_0 is the skin friction shear stress (or grain shear stress) and τ''_0 is the form drag-shear stress. The form resistance stems from the local flow separation and re-circulation in the lee of the dune. This partitioning of the shear stress is important for determining the proper estimation of the equivalent roughness height, which no longer is just attributable to Nikuradse's grain roughness. Additionally, knowledge of the grain shear stress is important for determination of the sediment transport rates, as the form shear stress is a result of pressure differences over the bedform (which are normal to the surface); although it has a major effect on the overall spatially distributed velocity distribution, it has no effect on the sediment transport.

As the focus of this research, making a proper determination of the velocity field in the presence of bedforms is important. Various theories and methods have been put forth to describe the velocity profiles and the proper methods to scale the velocity and distance from the bed with the roughness length and shear velocity; however, much of this work has been done at the laboratory scale. Similarity regions will be examined and proper scaling variables will be sought.

1.2. Present Study

1.2.1. Research Needs and Motivation

There has been much research conducted pertaining to the many issues related to the hydraulics and sediment transport in alluvial rivers (mean flow field, turbulence, shear partitioning, bedload transport, bedform geometry controls, etc). Much of this work has been conducted in laboratory flumes and small alluvial rivers. Of the field experiments, many of these are on small rivers and streams, with flows on the order of 200 m^3/s (i.e., Rio Grande, Niobrara, Rio Puerco, etc,). Obviously, there is a question of scale effects when theories or algorithms derived from laboratory research are applied to alluvial rivers (discharge ~ 2000 m^3/s), as it is difficult to extrapolate these results for large rivers. There is a need for data on large alluvial rivers to establish means for either enhancing existing theories (utilizing the laboratory data) or developing entirely new theories. Consider the following comments:

> *"this finding suggests that models that are significantly more accurate than those that have already been developed, including those presented herein, likely will not be forthcoming until more accurate and more comprehensive field and laboratory data are available."* Karim and Kennedy (1990)

> *"A large number of theoretical and empirical formulae exist to account for form drag due to bed forms, although few field studies have fully evaluate these formulae"* Dietrich and Whiting (1989)

> *"Field studies with detailed measurements of not only dune characteristics but also flow and transport are valuable and daunting for the same reason: they indicate the complexity of the real problem, which, together with practical constraints on field measurements, make more difficult the analysis and interpretation of the data."* ASCE Task Committee on Flow and Transport over Dunes (2002)

The lack of field-scale investigations conducted on large alluvial rivers has resulted from both the relative ease of collecting laboratory data and the difficulty in collecting field data, including the lack of experimental control.

For those previous studies collected at the large alluvial river scale (for example, Missouri, Mississippi, and Columbia Rivers), the investigators did not have the advantage of modern technology. Modern equipment, such as acoustic Doppler velocimeters (ADV), multi-phased array acoustic sounding devices (providing rapid 3-D images of the bed), optical backscatter sensors (OBS), and acoustic Doppler current profilers (ADCP), enable investigators today to collect data at scales (both time and space) that create tremendous opportunities for acquiring further knowledge. In addition, because of the size of instrumentation, it is now easier to collect data in the near-bed region of the flow (<0.5 m from the bed in 5 to10 m depths).

Proper understanding and prediction of the velocity profile and associated flow resistance is necessary for flow measurement, sediment transport prediction and modeling of alluvial systems. The combination and interaction of the turbulence field and flow accelerations because of the non-uniformity of the bed are said to affect the form drag of the bedforms (Nelson and others, 1993, p. 3944). In addition, the presence of sediment in the water column alters the density of the fluid and to some degree the viscosity. Any investigation into the flow field will need to assess the concentration and size distribution of the suspended sediment. Knowledge of the flow resistance is important for hydraulic engineers in solving various problems, with the most common problem being the determination of the relation between flow and stage.

The wake induced turbulence, non-uniform bed-induced acceleration, and the suspended-sediment induced density difference have effects on the velocity profile relation. Knowledge of the flow physics of the near-bed region is crucial. The near-bed region is an area of intense turbulence generation and concurrent mean flow energy loss. Because of difficulties of data collection at depth in large alluvial streams, the data are scant in the near-bed region. More detailed velocity data in the vicinity of bedforms are needed to gain increased understanding of the flow field in these areas. In addition, Muste (2001) highlights the need for more benchmark velocity profile data in sediment-laden flows to address effects of suspended sediment.

Finally, as turbulence and bed forms are such an inherent property of alluvial channel flows (Kennedy and Odgaard, 1991), quality data sets on the scales (both space and time) needed to characterize turbulence in large alluvial rivers are important but, unfortunately, very few and far between. It is hoped that the data collected during this study will be useful far beyond this dissertation research.

1.2.2.Goals and Objectives of Study

The goal of this work is to **examine the mean flow field at the scale of the large alluvial river with bedforms present for the purpose of determining appropriate**

dependencies, relations, and distributions of the flow field. Specific objectives are given below.

1. Collect field scale data over bedforms to evaluate the applicability of laboratory scale results to field scale problems.
2. Characterize the spatially averaged (longitudinal) mean velocity profile to both evaluate/verify present models and/or propose a new model.
3. Characterize the Reynolds stress distribution including the spatially-averaged Reynolds stress distribution and evaluate/verify present shear partitioning models.